

Population clustering as a signal for deconfinement in accreting compact stars

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ABSTRACT

We study the evolution of the rotation frequency for accreting compact stars. The discontinuous change of the moment of inertia of a rapidly rotating star due to the possible quark core appearance entails a characteristic change in the spin evolution. Numerical solutions have been performed using a model equation of state describing the deconfinement phase transition. Trajectories of spin evolution are discussed in the angular velocity - baryon number plane (*phase diagram*) for different accretion scenarios defined by the initial values of mass and magnetic field of the star, as well as mass accretion rate and magnetic field decay time. We observe a characteristic increase in the *waiting time* when a configuration enters the quark core regime. Overclustering of the population of Z sources of LMXBs in the phase diagram is suggested as a direct measurement of the critical line for the deconfinement phase transition since it is related to the behaviour of the moment of inertia of the compact star.

Subject headings: accretion, accretion disks — stars: evolution — stars: interiors — stars: magnetic fields — pulsars: general — X-rays: binaries

1. Introduction

The deconfinement phase transition into a plasma of quasifree quarks and gluons is expected to occur under conditions of sufficiently high temperatures and/or densities as, e.g., in heavy-ion collisions, a few microseconds after the big bang or in the cores of superdense stellar objects.

For the latter, signals of a phase transition have been suggested in the form of characteristic changes of observables (Weber 1999), such as the pulse timing (Glendenning, Pei & Weber 1997; Chubarian et al. 2000), brightness (Dar & DeRújula 2000) and surface temperature (Schaab et al. 1996; Blaschke, Grigorian & Voskresensky 2000) of the isolated pulsars during their evolution.

Recently, quasiperiodic brightness oscillations (QPOs) in low-mass X-ray binaries (LMXBs) have been observed (van der Klis 2000) which provide new mass and radius constraints for compact objects (Miller, Lamb & Psaltis 1998). According to the model of Stella and Vietri (Stella & Vietri 1999; Stella, Vietri & Morsink 1999) these constraints would allow only very compact objects made up of strange quark matter (Li et al. 1999). Due to the mass accretion flow these systems are candidates for the most massive compact stars at the limit to the formation of black holes. Therefore, if the possible deconfinement phase transition in compact stars exists at all, we expect it to occur in accreting LMXBs (Chubarian et al. 2000; Glendenning & Weber 2000).

In this paper we study the spin evolution of compact stars with possible quark matter cores for a disc accretion model and show that a pronounced signal of a deconfinement transition in the star interior can be obtained for accretors with long-lived magnetic fields and large angular momentum transfer. The so called Z sources of QPOs in LMXBs are suggested as objects which

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should predominantly populate the region of the suspected phase border between hadronic stars and quark core stars (QCSs) (Chubarian et al. 2000). We suggest this population clustering as a signal for deconfined quark matter in accreting compact stars.

2. Evolution in the $\Omega - N$ diagram

Our investigation is based on the classification of rotating compact star configurations in the plane of angular velocity Ω and baryon number N , the so called *phase diagram* (Blaschke, Grigorian & Poghosyan 2000).

We consider in our calculations a generic form of a relativistic equation of state with a deconfinement transition (Chubarian et al. 2000), which describes the hadronic matter by a Walecka model and the quark matter by a dynamical confinement model (Blaschke et al. 1999; Blaschke & Tandy 2000). The deconfinement phase transition is obtained by imposing Gibbs' conditions for phase equilibrium with the constraints that baryon number as well as electric charge of the system are globally conserved (Glendenning 1992). The onset of deconfinement (mixed phase) is obtained at a density of about 1.5 times the nuclear saturation density.

It has been shown that the critical line $N_{\text{crit}}(\Omega)$, which separates the region of QCSs from the hadronic ones, is correlated with the local maxima of the moment of inertia with respect to changes of the baryon number at given Ω due to the change of the internal structure of the compact object at the deconfinement phase transition. Therefore, we expect that the rotational behavior of these objects changes in a characteristic way when this line is crossed. The consequence will be an increase of the population of stars at this critical line which could be observed, provided that a sufficiently large number of accretors will be detected with their masses and spin frequencies (Blaschke, Grigorian & Poghosyan 2000).

We consider the spin evolution of a compact star under mass accretion from a low-mass companion star as a sequence of stationary states of configurations (points) in the phase diagram spanned by Ω and N . The process is governed by the change in angular momentum of the star

$$\frac{d}{dt}(I(N, \Omega) \Omega) = K_{\text{ext}}, \quad (1)$$

where

$$K_{\text{ext}} = \sqrt{GM\dot{M}^2 r_0} - N_{\text{out}} \quad (2)$$

is the external torque due to both the specific angular momentum transferred by the accreting plasma and the magnetic plus viscous stress given by $N_{\text{out}} = \kappa \mu^2 r_c^{-3}$, $\kappa = 1/3$ (Lipunov 1992). For a star with radius R and magnetic field strength B , the magnetic moment is given by $\mu = R^3 B$. The co-rotating radius $r_c = (GM/\Omega^2)^{1/3}$ is very large ($r_c \gg r_0$) for slow rotators. The inner radius of the accretion disc is

$$r_0 \approx \begin{cases} R, & \mu < \mu_c \\ 0.52 r_A, & \mu \geq \mu_c \end{cases}$$

where μ_c is that value of the magnetic moment of the star for which the disc would touch the star surface. The characteristic Alfvén radius for spherical accretion with the rate $\dot{M} = m\dot{N}$ is $r_A = (2\mu^{-4}GM\dot{M}^2)^{-1/7}$. Since we are interested in the case of fast rotation for which the spin-up torque due to the accreting plasma in Eq. (2) is partly compensated by N_{out} , eventually leading to a saturation of the spin-up, we neglect the spin-up torque in N_{out} which can be important only for slow rotators (Ghosh & Lamb 1979),

From Eqs. (1), (2) one can obtain the first order differential equation for the evolution of angular velocity

$$\frac{d\Omega}{dt} = \frac{K_{\text{ext}}(N, \Omega) - K_{\text{int}}(N, \Omega)}{I(N, \Omega) + \Omega(\partial I(N, \Omega)/\partial \Omega)_N}, \quad (3)$$

where

$$K_{\text{int}}(N, \Omega) = \Omega \dot{N}(\partial I(N, \Omega)/\partial N)_\Omega. \quad (4)$$

Solutions of (3) are trajectories in the $\Omega - N$ plane describing the spin evolution of accreting compact stars, see Fig. 1. Since $I(N, \Omega)$ exhibits characteristic functional dependences (Blaschke, Grigorian & Poghosyan 2000) at the deconfinement phase transition line $N_{\text{crit}}(\Omega)$ we expect observable consequences in the $P - P$ plane when this line is crossed.

In our model calculations we assume that both the mass accretion and the angular momentum transfer processes are slow enough to justify the assumption of quasistationary rigid rotation without convection. The moment of inertia of the rotating star can be defined as $I(N, \Omega) = J(N, \Omega)/\Omega$, where $J(N, \Omega)$ is the angular momentum of the star. For a more detailed description of the method and analytic results we refer to (Chubarian et al. 2000) and the works of Hartle (1967); Hartle & Thorne (1968), as well as Sedrakian & Chubarian (1968a,b).

The time dependence of the baryon number for the constant accreting rate \dot{N} is given by

$$N(t) = N(t_0) + (t - t_0)\dot{N}. \quad (5)$$

For the magnetic field of the accretors we consider the exponential decay (Bhattacharya & van den Heuvel 1979)

$$B(t) = [B(0) - B_\infty] \exp(-t/\tau_B) + B_\infty. \quad (6)$$

We solve the equation for the spin-up evolution (3) of the accreting star for decay times $10^7 \leq \tau_B[\text{yr}] \leq 10^9$ and initial magnetic fields in the range $0.2 \leq B(0)[\text{TG}] \leq 4.0$. The remnant magnetic field is chosen to be $B_\infty = 10^{-4}\text{TG}^1$ (Page, Geppert & Zannias 2000).

At high rotation frequency, both the angular momentum transfer from accreting matter and the influence of magnetic fields can be small enough to let the evolution of angular velocity be determined by the dependence of the moment of inertia on the baryon number, i.e. on the total mass. This case is similar to the one with negligible magnetic field considered in (Shapiro & Teukolsky 1983; Burderi et al. 1999; Chubarian et al. 2000) where $\mu \leq \mu_c$ in Eq. (3), so that only the so called internal torque term (4) remains.

In Fig. 1 we show evolutionary tracks of accretors in phase diagrams (left panels) and show the corresponding spin evolution $\Omega(t)$ (right panels). In the lower panels, the paths for possible spin-up evolution are shown for accretor models initially having a quark matter core ($N(0) = 1.55 N_\odot$, $\Omega(0) = 1 \text{ Hz}$). The upper panels show evolution of a hybrid star without a quark matter core in the initial state ($N(0) = 1.4 N_\odot$, $\Omega(0) = 1$

Hz), containing quarks only in mixed phase. We assume a value of \dot{N} corresponding to observations made on LMXBs, which are divided into Z sources with $\dot{N} \sim 10^{-8} N_\odot/\text{yr}$ and A(toll) sources accreting at rates $\dot{N} \sim 10^{-10} N_\odot/\text{yr}$ (Glendenning & Weber 2000; Bhattacharya & van den Heuvel 1979; van der Klis 2000).

For the case of a small magnetic field decay time $\tau_B = 10^7 \text{ yr}$ (solid and dotted lines in Fig.1) the spin-up evolution of the star cannot be stopped by the magnetic braking term so that the maximal frequency consistent $\Omega_{\text{max}}(N)$ with stationary rotation can be reached regardless whether the star did initially have a pure quark matter core or not.

For long lived magnetic fields ($\tau_B = 10^9 \text{ yr}$, dashed and dot-dashed lines in Fig.1) the spin-up evolution deviates from the monotonous behaviour of the previous case and shows a tendency to saturate. At a high accretion rate (dot-dashed lines) the mass load onto the star can be sufficient to transform it to a black hole before the maximum frequency could be reached whereas at low accretion (dashed lines) the star spins up to the Kepler frequency limit.

3. Waiting time and population clustering

The question arises whether there is any characteristic feature in the spin evolution which distinguishes trajectories that traverse the critical phase transition line from those remaining within the initial phase.

For an accretion rate as high as $\dot{N} = 10^{-8} N_\odot/\text{yr}$ the evolution of the spin frequency in Fig. 1 shows a plateau where the angular velocity remains within the narrow region between $2.1 \leq \Omega[\text{kHz}] \leq 2.3$ for the decay time $\tau_B = 10^9 \text{ yr}$ and between $0.4 \leq \Omega[\text{kHz}] \leq 0.5$ when $\tau_B = 10^7 \text{ yr}$. This plateau occurs for stars evolving into the QCS region (upper panels) as well as for stars remaining within the QCS region (lower panels). This saturation of spin frequencies is mainly related to the compensation of spin-up and spin-down torques at a level determined by the strength of the magnetic field. In order to perform a more quantitative discussion of possible signals of the deconfinement phase transition we present in Fig. 2 trajectories of the spin-up evolution in the $\dot{P}-P$ plane for stars with $N(0) = 1.4 N_\odot$ and $\Omega(0) = 1 \text{ Hz}$ in the initial state; the four sets of accretion

¹1 TG= 10^{12} G

rates and magnetic field decay times coincide with those in Fig. 1.

When we compare the results for the above hybrid star model (solid lines) with those of a hadronic star model (quark matter part of the hybrid model omitted; dotted lines) we observe that only in the case of high accretion rate ($\dot{M} = 10^{-8} N_{\odot}/\text{yr}$, e.g. for Z sources) and long-lived magnetic field ($\tau_B = 10^9 \text{yr}$) there is a significant difference in the behaviour of the period derivatives. The evolution of a star with deconfinement phase transition shows a dip in the period derivative in a narrow region of spin periods. This feature corresponds to a plateau in the spin evolution which can be quantified by the *waiting time* $\tau = |P/\dot{P}| = \Omega/\dot{\Omega}$. In Fig. 3 (lower and middle panels) we present this waiting time in dependence on the rotation frequencies $\nu = \Omega/(2\pi)$ for the relevant case labeled (9,-8) in Figs. 1,2. The comparison of the trajectory for a hybrid star surviving the phase transition during the evolution (solid line) with those of a star evolving within the hadronic and the QCS domains (dotted line and dashed lines, respectively), demonstrates that an enhancement of the waiting time in a narrow region of frequencies is a characteristic indicator for a deconfinement transition in the accreting compact star.

The position of this peak in the waiting time depends on the initial value of magnetic field, see Fig. 3. In the middle and lower panels of that Figure, we show the waiting time distribution for $B(0) = 0.75 \text{ TG}$ and $B(0) = 0.82 \text{ TG}$, respectively. Maxima of the waiting time in a certain frequency region have the consequence that the probability to observe objects there is increased (*population clustering*). In the upper panel of this Figure the spin frequencies for observed Z sources in LMXBs with QPOs (van der Klis 2000) are shown for comparison. In order to interpret the clustering of objects in the frequency interval $225 \leq \nu[\text{Hz}] \leq 375$ as a phenomenon related to the increase in the waiting time, we have to choose initial magnetic field values in the range $1.0 \geq B(0)[\text{TG}] \geq 0.6$ for the scenario labeled (9,-8), see also the dashed lines in Fig.2.

4. Signal for Deconfinement in LMXBs

The results of the previous section show that the waiting time for accreting stars along their evolution trajectory is larger in a hadronic configuration than in a QCS, after a time scale when the mass load onto the star becomes significant. This suggests that if a hadronic star enters the QCS region, its spin evolution gets enhanced thus depopulating the higher frequency branch of its trajectory in the $\Omega - N$ plane.

In Fig. 4 we show contours of waiting time regions in the phase diagram. The initial baryon number is $N(0) = 1.4 N_{\odot}$ and the initial magnetic field is taken from the interval $0.2 \leq B(0)[\text{TG}] \leq 4.0$.

The region of longest waiting times is located in a narrow branch around the phase transition border and does not depend on the evolution scenario after the passage of the border, when the depopulation occurs and the probability to find an accreting compact star is reduced. Another smaller increase of the waiting time and thus a population clustering could occur in a region where the accretor is already a QCS. For an estimate of a population statistics we show the region of evolutionary tracks when the values of initial magnetic field are within $0.6 \leq B(0)[\text{TG}] \leq 1.0$ as suggested by the observation of frequency clustering in the narrow interval $375 \geq \nu[\text{Hz}] \geq 225$, see Fig. 3.

As a strategy of search for QCSs we suggest to select from the LMXBs exhibiting the QPO phenomenon those accreting close to the Eddington limit (Bhattacharya & van den Heuvel 1979) and to determine simultaneously the spin frequency and the mass (Lamb & Miller 2000) for sufficiently many of these objects. The emerging statistics of accreting compact stars should then exhibit the population clustering shown in Fig. 4 when a deconfinement transition is possible. If a structureless distribution of objects in the $\Omega - N$ plane will be observed, then no firm conclusion about quark core formation in compact stars can be made.

For the model equation of state on which the results of our present work are based, we expect a baryon number clustering rather than a frequency clustering to be a signal of the deconfinement transition in the compact stars of LMXBs. The model independent result of our study is that a population clustering in the phase diagram for ac-

creting compact stars shall measure the critical line $N_{\text{crit}}(\Omega)$ which separates hadronic stars from QCSs where the shape of this curve can discriminate between different models of the nuclear EoS at high densities.

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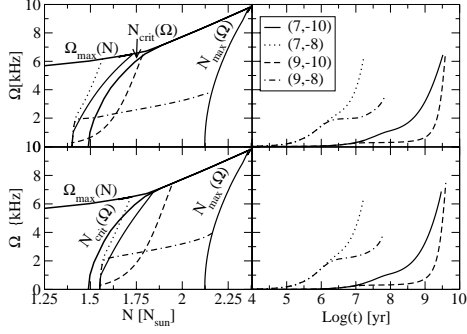


Fig. 1.— Spin evolution of an accreting compact star for different decay times of the magnetic field and different accretion rates. Upper panels: initial configuration with $N(0) = 1.4 N_{\odot}$; Lower panels: $N(0) = 1.55 N_{\odot}$; $\Omega(0) = 1$ Hz in both cases. The numbers in the legend box stand for $(\log(\tau_B[\text{yr}]), \log(\dot{N}[N_{\odot}/\text{yr}])$. For instance (9,-8) denotes $\tau_B = 10^9$ yr and $\dot{N} = 10^{-8} N_{\odot}/\text{yr}$.

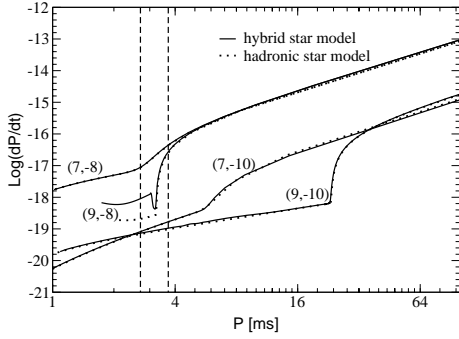


Fig. 2.— Spin-up evolution of accreting compact stars in the $\dot{P} - P$ diagram. For labels and initial values see to Fig. 1. The region of the vertical dashed lines corresponds to the clustering of periods observed for LMXBs with QPOs. A dip (waiting point) occurs at the deconfinement transition for parameters which correspond to Z sources ($\dot{N} = 10^{-8} N_{\odot}/\text{yr}$) with slow magnetic field decay ($\tau_B = 10^9 \text{yr}$).

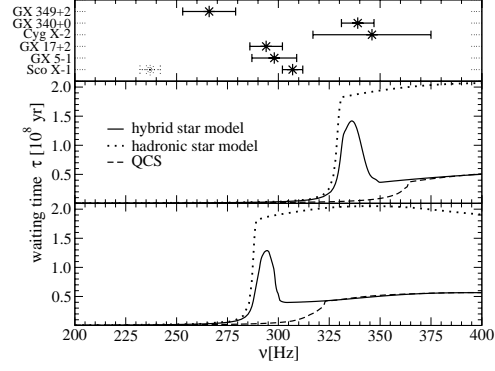


Fig. 3.— *Upper panel*: frequency interval for observed Z source LMXBs (van der Klis 2000); *middle panel*: waiting times $\tau = P/\dot{P}$ for scenario (9,-8) and initial magnetic field $B(0) = 0.75$ TG; *lower panel*: same as middle panel for $B(0) = 0.82$ TG. Spin evolution of a hybrid stars (solid lines) shows a peak in the waiting time characteristic for the deconfinement transition. Hadronic stars (dotted lines) and QCSs (dashed lines) have no such structure.

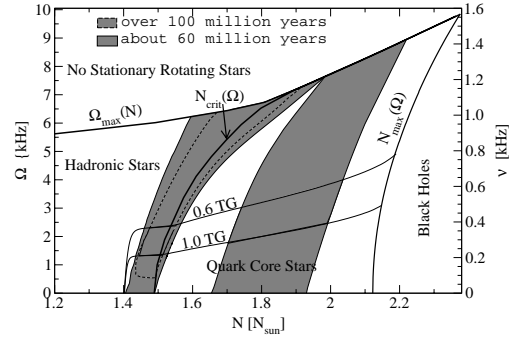


Fig. 4.— Regions of waiting times in the phase diagram for compact hybrid stars for the (9,-8) scenario. For an estimate of a population statistics we show the region of evolutionary tracks when the interval of initial magnetic field values is restricted to $0.6 \leq B(0) [\text{TG}] \leq 1.0$. Note that the probability of finding a compact star in the phase diagram is enhanced in the vicinity of the critical line for the deconfinement phase transition $N_{\text{crit}}(\Omega)$ by at least a factor of two relative to all other regions in the phase diagram.